EXECUTIVE SUMMARY

Background: California has persistent air quality problems that affect the health of millions of residents. Global climate change will modify long-term weather patterns in California with direct consequences to air quality and public health. California's diverse emissions sources located inside air basins bordered by mountain ranges require analysis at fine spatial resolution (<10km) while at the same time the long-term El-Nino Southern Oscillation (ENSO) patterns require 7-8 year analysis periods for meaningful analysis. Rigorous evaluations that address both of these issues are needed to accurately assess climate impacts on air quality in California.

Jacob and Winner [1] recently reviewed studies seeking to quantify climate change impacts on regional air quality. They identify three major classes of study methods: (i) statistical downscaling, (ii) model perturbations, and (iii) dynamic downscaling. Statistical downscaling uses historical relationships between meteorology and air quality to predict future changes in ozone (O_3) and airborne particulate matter (PM) concentrations based on changes to meteorology alone. Model perturbation studies alter the meteorological inputs used in regional air quality models in a manner that is consistent with future climate change. Full dynamic downscaling uses Global Climate Model (GCM) predictions as initial/boundary conditions for regional weather models that are then coupled to air quality models to more accurately balance the simultaneous modifications to meteorological variables that are likely to occur because of climate change. Each of these study designs has strengths and weaknesses for ozone and PM analysis in California.

Methods: The three study methods identified by Jacob and Winner [1] were employed to analyze climate change impacts on ground-level O_3 and PM concentrations in California (see Table 1).

Table 1: Summary of methods employed to study climate impacts on California air quality and the chapters documenting results.

	Pollutant	
Study Method	O_3	PM
Statistical Downscaling	Chapter 4	Not Applicable
Perturbation Studies	Chapters 2,3	Chapter 2
Dynamic Downscaling	Not Applicable	Chapters 5-10

Statistical downscaling studies for PM concentrations could not be carried out because robust linear relationships between meteorological variables and PM concentrations do not exist for California's air basins. Dynamic downscaling studies for O_3 could not be carried out because summertime wind speed was over-predicted by the downscaling methods, leading to excess ventilation and under-predicted basecase O_3 concentrations. This issue does not severely impact annual-average PM predictions because summer-time PM concentrations are typically much lower than concentrations in other seasons.

Model perturbation studies based on changing the meteorology during historical episodes were feasible for both O_3 and PM and so these studies were used for a preliminary analysis of climate effects on air quality in California. Statistical downscaling was then used to transform results from the GFDL Global Climate Model into an O_3 assessment between the years 2000 – 2100. The foundation for this analysis was the strong correlations between surface ozone concentrations and the air temperature at a height of 850 millibars (T850). Dynamic downscaling of the PCM Global Climate Model using the Weather Research Forecast (WRF) meteorological model, the UCD/CARB/SCAQMD emissions system, and the UCD air quality model was then used for the future PM assessment. Climate-induced changes to PM concentrations were calculated regionally and using population-weighted concentrations. The uncertainty of the comparison between current and future climate was quantified using the inter-annual variability within the same climate periods.

Ozone Results: Perturbation studies for historical O_3 episodes suggest that concentrations increase when maximum daytime temperatures increase. Since the majority of Global Climate Models predict that future climate will be warmer than current climate in California, a "climate penalty" exists for ground level O_3 concentrations as summarized in Figure 1 for the South Coast Air Basin (SoCAB).

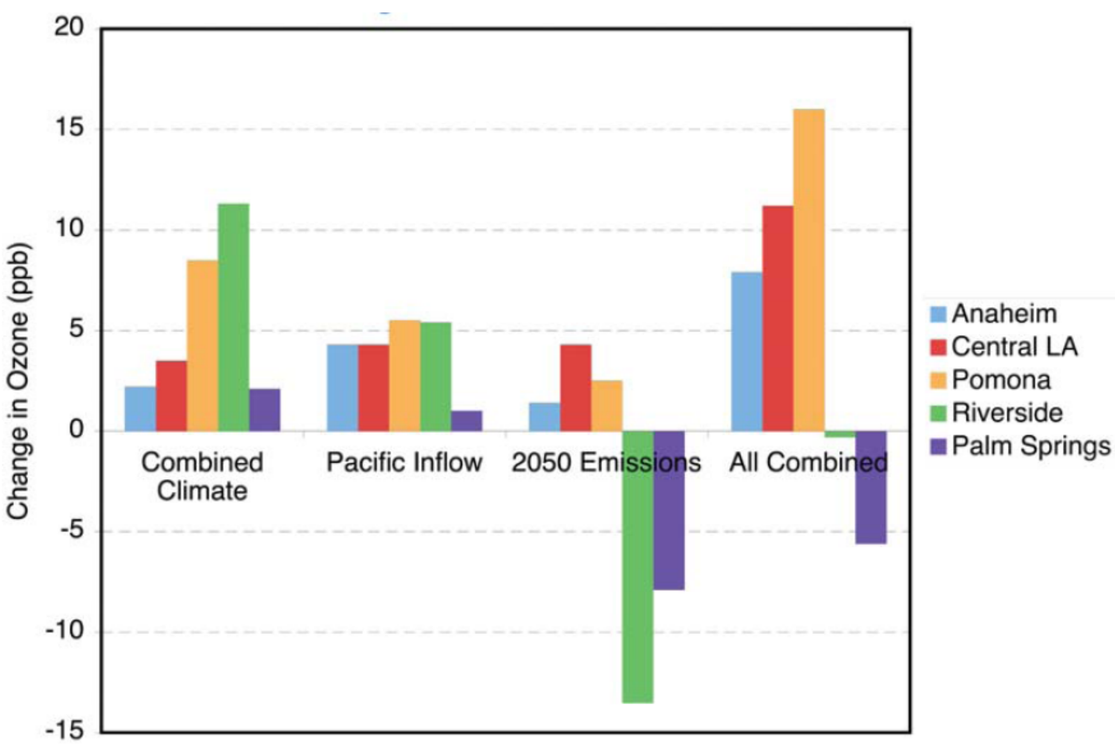

Figure 1: Average weekday ozone (ppb) at 1500 h LT (local time) for a SoCAB episode in 2005: base case levels and differences between specified run and base case.

Both statistical downscaling and model perturbation studies confirm that the magnitude of the climate penalty for O_3 depends on the base emissions year used for the evaluation, with larger penalties calculated for more reactive emissions (older episodes) and smaller penalties for less reactive emissions (newer episodes) as shown in Figure 2 for the SoCAB.

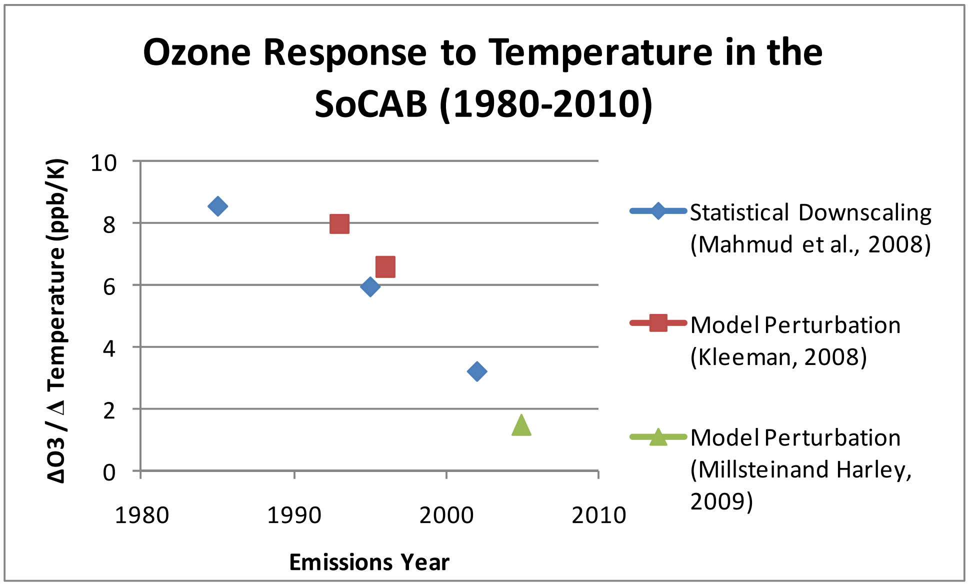

Figure 2: Evolution of the O_3 climate penalty over time due to changes in the emissions inventory in the South Coast Air Basin (SoCAB).

Perturbation studies also show that O_3 concentrations are insensitive to changes in nighttime temperatures. Nighttime temperatures in California have increased more than daytime temperatures over the past several decades, but future changes may not follow this pattern. Maximum daytime temperatures at a height of ~1.5 km (T850) over the San Joaquin Valley (SJV) and South Coast Air Basin (SoCAB) are predicted to increase according to most Global Climate Models, including the Geophysical Fluid Dynamics Laboratory (GFDL) model developed at Princeton. The correlation slope between surface O_3 concentrations and T850 is robust under fixed emissions conditions. Statistical downscaling suggests that by the year 2050 California would experience an additional 22-30 days year^{-1} and 6-13 days year^{-1} with ozone concentrations ≥90 ppb under the IPCC A2 and B1 emissions scenarios (assuming emissions of criteria pollutants in California remained at 1990-2004 levels). Note that ENSO cycles introduce inter-annual variability in these results, but the upward trend over several decades is unmistakable.

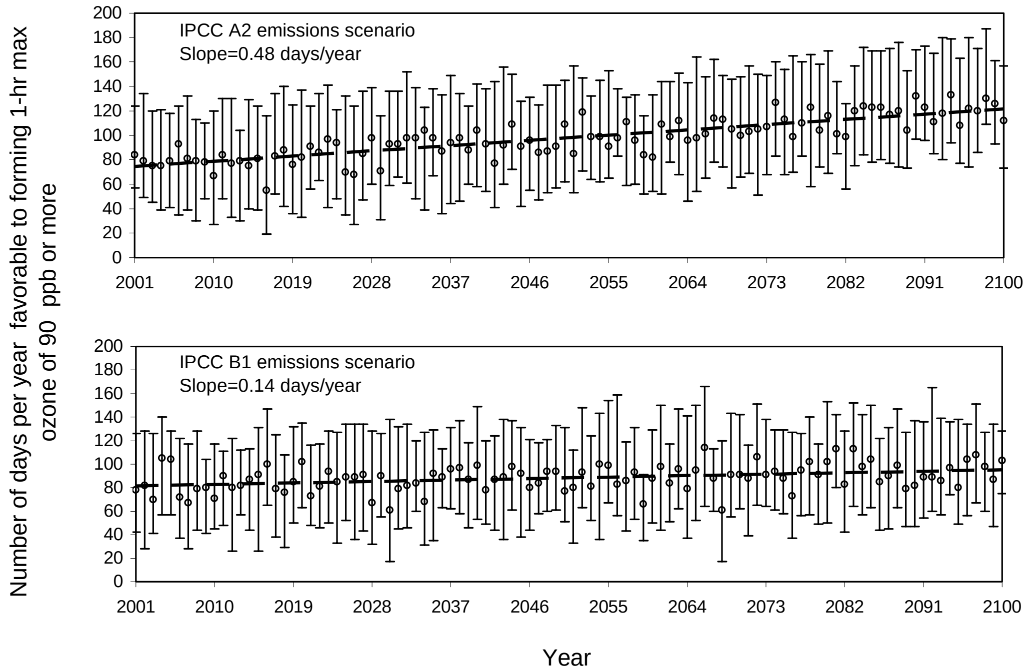

Figure 3: The number of days per year conducive to forming 1-hr maximum ozone of 90 ppb or more at Upland, CA under the Intergovernmental Panel on Climate Change (IPCC) emissions scenarios: A2 (top panel) and B1 (bottom panel). Note that the underlying assumption for this prediction is that the criteria emissions in CA remain at the 1990-2004 level. Uncertainty bars represent the third and the first quartiles of the predicted number of days.

PM Results: Model perturbation studies for PM concentrations in California were inconclusive. Increasing temperature increases the production rate of semi-volatile reaction products but decreases partitioning to the condensed phase. Increased humidity and ozone concentrations generally promote increased condensation of ammonium nitrate but increased precipitation events quickly scavenge airborne particulate matter. These competing trends clearly point out the need for full dynamic downscaling of model predictions.

Dynamic downscaling of PCM global results to 4 km resolution over California predicts that average surface air temperatures over California will increase by 1-2K between 2047-53 and 2000-06 ($p<0.05$). Average wind speeds are predicted to increase during the winter in coastal regions of California ($p<0.1$) but change little in other seasons or locations. The strength of the atmospheric stagnation events is predicted to increase in the future during all seasons except for spring.

Model predictions for $PM_{2.5}$ mass and component concentrations between the years 2000-06 were biased ~30% lower than measurements because the wind speeds predicted by WRF were biased high by 2-3 ms^{-1} during stagnation events. Positive wind speed bias largely results from excessive transfer of momentum into the surface layer, compounded by the fact that the predictions cannot be constrained by assimilation of actual measurements (that do not exist for climate simulations). Overall, the bias introduced by the wind speed over-prediction should be consistent between present and future analysis periods so that the comparison between periods is meaningful.

Average $PM_{2.5}$ mass concentrations are predicted to decrease in coastal California but increase slightly in the northern SJV between 2000-06 and 2047-53. A corresponding analysis of the inter-annual variability indicates that only the changes in the coastal areas are significant at the 95% confidence level, meaning that other regions may experience little impact on $PM_{2.5}$ mass due to climate change.

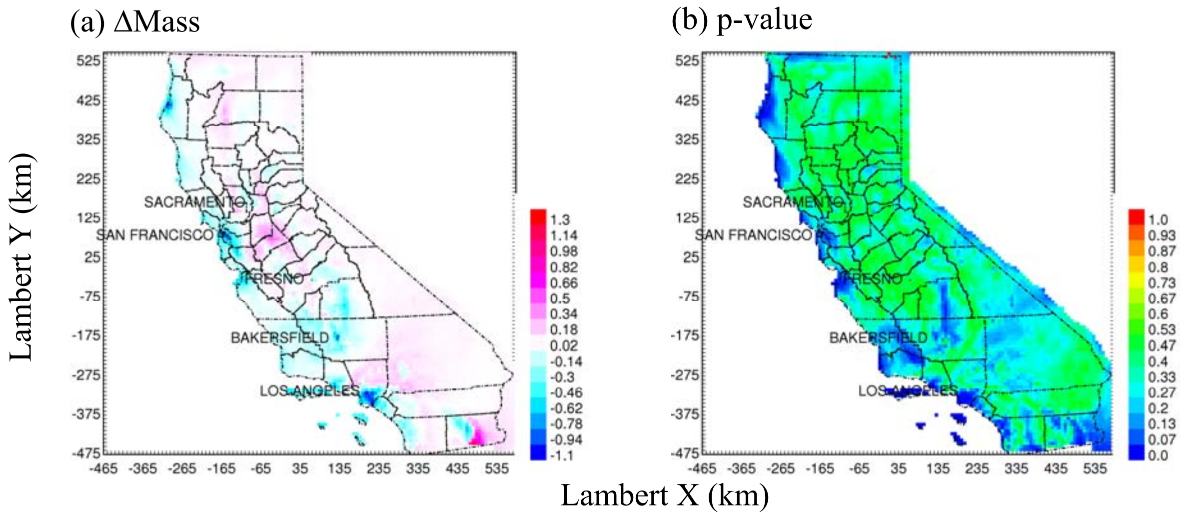

Figure 4: Changes in annual average $PM_{2.5}$ mass concentrations and corresponding p-values in CA likely to occur in the future (2047-53) due to climate change from the present-day (2000-06). The p-value quantifies the likelihood that average future concentrations are equal to present day concentrations.

The majority of the decreased average $PM_{2.5}$ concentrations were associated with reductions in primary PM constituents (due to increased average ventilation) and secondary ammonium nitrate (due to increased ventilation and increased temperature).

Annual-average population-weighted $PM_{2.5}$ mass differences between 2047-53 and 2000-06 are small relative to the uncertainty introduced by inter-annual variability. Individual source contributions to PM mass do respond to climate in a statistically significant manner (95% CI does not overlap zero). Future population-weighted annual-average primary $PM_{2.5}$ from shipping and combustion of high sulfur fuel both decrease by ~6% in response to climate change.

Extreme $PM_{2.5}$ mass concentrations (predicted on the 1% of days with the highest overall concentrations) are predicted to increase by 7-20 μg m^{-3} in the SJV between 2000-06 and 2047-53 due to the increased strength of future stagnation events. The inter-annual variability of the $PM_{2.5}$ mass during extreme events is large, leading to broad confidence intervals on the climate signal for total PM mass. Once again, climate signals are more evident for primary source contributions that contribute to overall mass. Extreme 99th

percentile population-weighted $PM_{2.5}$ primary source contributions from diesel engines increase by 28% response to future climate change. Emissions controls such as diesel particle filters or bans on residential wood combustion are effective methods to offset the climate penalty for $PM_{2.5}$ during extreme pollution events.

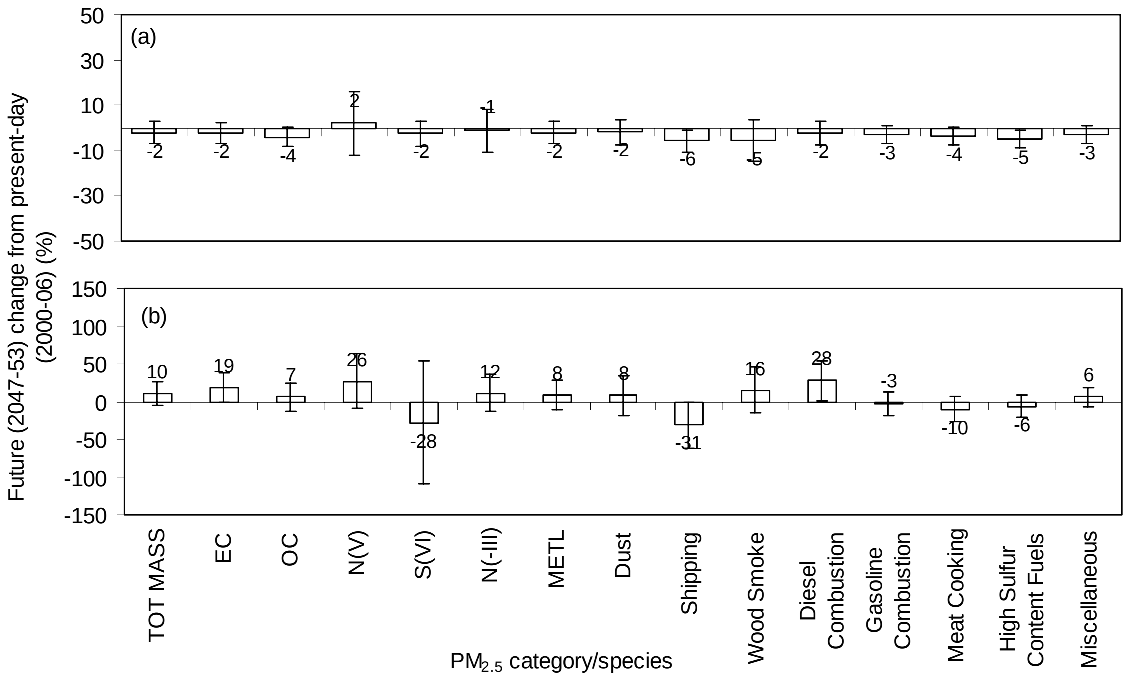

Figure 5: Future (2047-53) minus present (2000-06) change in population-weighted $PM_{2.5}$ total mass, components, and primary source categories for (a) annual averages and (b) 99th percentile extreme pollution events. Results are averaged across the entire state of California. The error bars represent the 95% confidence interval.

Conclusions: Statistical downscaling and model perturbation studies for ozone consistently indicate that climate change will produce conditions more conducive to ozone production in California. The magnitude of the "climate penalty" for ozone is decreasing over time due to the changes occurring in the criteria pollutant emissions inventory. Additional emissions controls are currently needed to offset the climate "penalty". The magnitude of the additional emissions controls needed in the future depends on our progress towards achieving air quality standards.

Dynamic downscaling techniques indicate that the effect of climate change on PM concentrations is likely to be smaller than the inter-annual variability experienced during any seven year analysis window. Longer analysis times are needed to quantify a climate signal different from zero with 95% confidence across a broad array of PM metrics.

Evidence from over 4000 simulated days in the current study suggests that climate change will reduce annual-average primary PM_{10} / $PM_{2.5}$ / $PM_{0.1}$ concentrations but increase extreme 99th percentile primary PM_{10} / $PM_{2.5}$ / $PM_{0.1}$ concentrations in the state of California.

Future Work: The economic consequences of known climate impacts in California are estimated to be \$31-57B [2], with another \$8B of estimated costs needed to offset potential air quality impacts [2]. The model perturbation analysis for ozone that is summarized in this final report provides part of the foundation for this latter estimate, but significant uncertainty remains about the economic costs associated with changes to extreme PM concentrations. Future studies should quantify the economic impacts associated with extreme concentration events in California.

The 7 year analysis periods for dynamic downscaling exercises should be expanded to ~10 years to reduce the uncertainty bounds of the climate signal on PM concentrations in California. Furthermore, an ensemble of simulations should be conducted using different models to fully quantify the uncertainty in the calculation (which is larger than the inter-annual variability predicted by a single modeling system).

The shortcomings in the meteorological models that prevent accurate downscaling during winter months without data assimilation should be corrected so that dynamic downscaling studies can be carried out for ozone concentrations in California.

Future studies should incorporate emissions reductions associated with California Assembly Bill 32 (AB32) into the future inventories and take care to properly scale power generation, chemical processing, and goods movement sources as a function of economic condition.